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Simulation of radiation damage in fusion reactor first wall material by an accelerator based neutron source

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Abstract : Radiation damage problem for the structural material surrounding fusion plasma in a fusion reactor will be the crucial bottleneck in the commercial utilisation of fusion energy. It is expected that the structural material in the first wall and the blanket structures will be exposed to an intense flux of 14 MeV neutrons at an elevated temperature which will create vacancies and interstitials, defect clusters, dislocation loops etc. The problem is further complicated by the fact that compared to fission neutrons, these energetic fusion neutrons will produce ten times more hydrogen, helium and other transmutation product which will affect the physico-chemical property of the material in a significant way. For reliable and safe utilisation of fusion power we need to develop materials which will withstand such an intense radiation environment. It is shown that the present day devices which are being used to simulate fusion radiation environment for materials development are insufficient and inadequate Therefore we explore the possibility of using spallation neutrons which can be obtained using high energy accelerators.

Keywords : Fusion, simulation, accelerator, radiation damage, spallation.

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1. Introduction

Reliable and safe operation of a fusion reactor requires extensive testing of the materials used in its construction, particularly the first wall construction material. The absence of adequate materials for construction of commercial fusion devices will seriously impede the development of fusion reactors and might ultimately be one of the crucial bottlenecks in the commercial utilisation of fusion energy. It is expected that the structural material in the first wall and the blanket structures will be exposed to an intense flux of 14 MeV neutrons at elevated temperatures while under cyclic stresses. The collisions of these energetic neutrons may eject atoms from their normal lattice sites, creating vacancies and interstitials, point defect clusters and dislocation loops which all influence a number of physical properties to various degrees. During the lifetime of a reactor each atom in the first wall material will on the average have been displaced of the order of a hundred times. The radiation damage produced by the neutrons is compounded by the fact that the production cross section of transmutation products is very high for these 14 MeV neutrons, higher by one to two orders of magnitude compared to fission neutrons. These transmutation reactions, in particular for helium and hydrogen, are sufficiently numerous to cause appreciable compositional changes in the materials and hence affect their physico-chemical properties. The magnitude of the problem can be estimated from the fact that for the same amount of energy a fusion reaction produces about 5 times more neutrons compared to fission reaction and since these neutrons are much more energetic compared to those in the fission reaction they produce much higher lattice damage, helium, hydrogen and other transmutation products. Since radiation damage is a nonlinear function of fluence and depends on a number of competing phenomena, it is not possible estimate damage effects by extrapolating from low dose irradiations. Therefore, in order to study the radiation effect in materials for fusion application we need a device which is capable of producing intense source of high energy neutrons which can produce damage effects at the same or preferably at an order of magnitude higher rate so that a suitable material could be ready before the design of a commercial fusion reactor begins. It has been estimated by several study groups that a fusion reactor is expected to be economical at a integrated dose of about 300-400 dpa or a net fluence of $\sim 10^{23}$ n/cm^2. This means that we must employ for the development of materials for fusion reactors a neutron source which is capable of delivering fluxes of the order of 10^{16} n/cm^2/sec. Ideally a high intensity 14 MeV neutron source or a compact fusion device with a high magnetic field and a large β will produce a 14 MeV neutron flux which would be an order of magnitude larger than those expected in a large commercial fusion device. The feasibility of such a fusion device itself is doubtful. Therefore the radiation environment of a fusion reactor must be "simulated" for the testing of materials. Existing simulation devices such as fission reactors or neutrons from D-Li or D-Be reactions or heavy ions are inadequate for a commercial material development programme for fusion applications. This paper examines a recently proposed simulation device (Kley and Bishop 1985) which utilises spallation neutrons produced by interaction of high energy protons obtained from accelerators with lead target. We discuss various parameters for radiation damage simulation such as He to dpa ratio, volume of irradiation, lifetime dose for materials and nature of displacement damage and compare the radiation environment of accelerator based neutron source with the neutron radiation environment of first wall of a fusion reactor. It is shown that such an accelerator based neutron source fulfils most of the criteria of an ideal simulation device.

2. Intercomparison of various simulation devices

There are a number of simulation devices which are currently being used to simulate the radiation environment surrounding fusion plasma. Some of them are : (i) Relativistic electrons from high voltage electron microscope (HVEM), (ii) Heavy ions, (iii) light ions such as p, d, α from cylotrons, (iv) High energy photon beam from high energy accelerators such as LAMPF or SIN, (v) Fast and mixed spectrum fission reactors such as HFIR, ORR, FFTF etc., (vi) Accelerator based neutron sources such as (a) RTNS-II-a 14 MeV neutron source, (b) D-Be neutron source, (c) FMIT-a D-Li neutron source etc. Before commenting on the adequacy of these devices for simulation of radiation environment of fusion plasma, we enumerate some of the criteria that are generally used to compare various simulation devices.

The important parameters used in intercomparing various simulation devices, are listed below (i) Appm/Dpa : The ratio of atom parts per million to the displacement rate is one of the most crucial parameters while comparing various simulation devices. Even though the usefulness of this parameter for intercomparing different simulation devices has been questioned, it is widely used as a parameter characterising a simulation device. For fusion spectrum He/Dpa ratio has been estimated to be about 10 for SS-316 though for DIN 1.4914 value of 30 has been quoted for CCTR-II spectrum. (ii) Displacement rate : It is clear that in order to develop materials for fusion in a shortest possible time, the simulating device must achieve the lifetime dose, which is about 400 dpa, at a fast rate. (iii) He production rate : He generation at elevated temperatures has got a crucial impact on the mechanical properties of the materials causing embrittlement and enhanced swelling. (iv) Hydrogen production rate : Hydrogen production in materials has also got significant bearing on the physical properties of materials, though because of high mobility and solubility it is not expected to cause materials problem on the same scale as in the case of helium. (v) Transmutation product : The effect of foreign element on the mechanical property of a material is well known. Since a large amount of transmutation products are generated in fusion spectrum, any simulation device for materials development for fusion must also generate transmutation products on similar level. (vi) Primary recoil spectra : The nature of primary recoil spectrum determines the damage characteristics. Therefore it is necessary that a simulation device must not produce recoil spectrum very different from fusion spectra. (vii) Volume of irradiation : The need to test several hundreds of samples of different materials before selecting the best one requires that the available volume of irradiation must be adequate, preferably several litres.

Fission reactors such as fast breeder EBR-II or mixed spectrum reactors such as HFIR or ORR have been some of the traditional tools for materials development for nuclear applications. These reactors have required volume and neutron fluxes which are comparable to fusion reactors. The main disadvantage has been in softness of spectrum compared to fusion spectrum resulting in much lower He, Hydrogen and transmutation product formation. Even use of mixed spectrum reactors such as HFIR has He/Dpa ratio which agress with fusion values at only one point of time due to non linearity of He generation. At higher Dpa it differs by order of magnitude from fusion values.

2.1. *Application of accelerators :*

Charged particles from accelerators have been another tool for materials development. Electrons from high voltage electron microscope are often used in creating and simultaneous study of damage. The main disadvantage of this method is the very soft primary recoil spectrum, no generation of hydrogen, helium or transmutation products typical of fusion spectrum. The sample thickness is very small in such experiments. Heavy ion beams also suffer from similar disadvantages even though very high dpa rates can be obtained from such beams. Light ions such as p, d or α of energies around 50 MeV from cyclotrons have adequate dpa rate. But again the primary recoil spectrum is very different, coupled with differences in He, Hydrogen and transmutation production rate. The sample thickness is small for any mechanical testing. Even very high energy proton beam of energies 600-800 MeV which have ranges around 25-30 cms in Fe are not adequate for a commercial alloy development program. The reason is that due to excessive sample heating, the sample size is still limited to 100-200 microns. The transmutation product formation is several orders of magnitude higher coupled with very different reoil spectrum. These considerations have focussed attention on the use of neutrons generated by the interaction of the charged particles from accelerators instead of charged particles themselves.

2.2. *Accelerator based neutron sources :*

In 1976 three American projects to use accelerator based neutron sources were started. These are (i) RTNS-A 400 KeV, 150 mA beam of deutrons impinging on rotating water cooled TiT target generating 14 MeV neutrons. This device even though having ideal characteristics so far as the spectrum is concerned, is still limited by low flux $\sim 10^{13}$ n/cm^2/sec which is three orders of magnitude less than the required dose. Moreover the available sample space is less than $\sim$1 cm^3. This source is primarily meant to correlate damage structure from other simulation devices with those produces by 14 MeV neutrons. (ii) INS – This project envisaged use of 1-3 mA triton beam on supersonic jet of deuterium gas target. It was estimated that the maximum attainable flux will be 10^{14} n/cm^2/sec in a small volume which is still short of required flux of 10^{16} n/cm^2/sec. This project was cancelled due to these reasons. (iii) FMIT – This simulation device proposed to use of a 100 mA deutron beam of 35 MeV energy on a lithium jet target. The neutron flux generated by stripping reaction in this source was estimated to be 10^{15} n/cm^2/sec with a dpa of about 80 per year. The neutron flux is peaked around 14 MeV. However the available volume space where dpa was estimated to be high ($\sim$80) is only 10 cm^3. Therefore despite having high source strength and good spectrum characteristics, this project was finally cancelled in 1986.

3. Spallation neutron sources

First systematic studies of using spallation neutrons for fusion material testing was proposed by Kley and Bishop (1985) even though there have been some preliminary survey by some other groups. The proposal of Kley and Bishop is for a spallation neutron source (SNS) which is to be called EURAC based on a 600 MeV, 6 mA beam of protons impinging on liquid lead target. We have carried out detailed design studies for this neutron source. For the purpose of calculation we have used a simplified geometry shown in Figure 1.

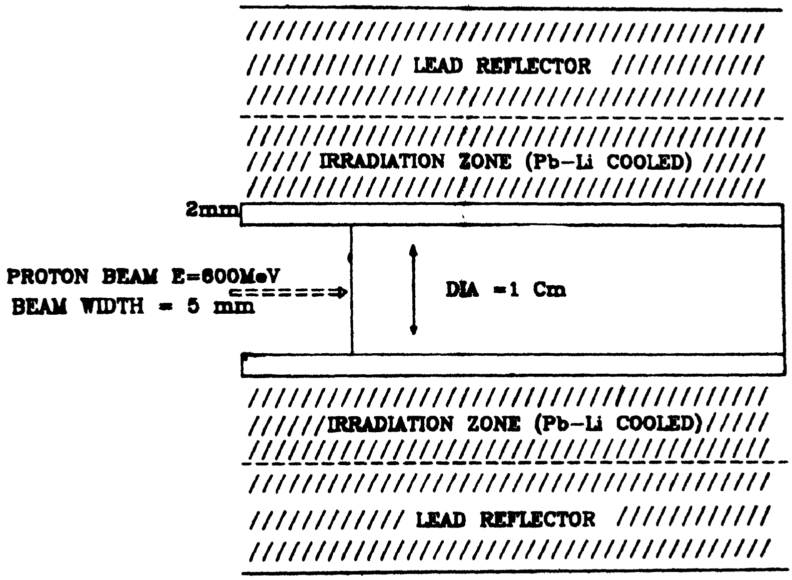

Figure 1. Simplified target-reflector assembly (not to scale).

The central portion represents a 1 cm diameter lead target of 50 cm length. Surrounding this target is a 2 mm iron cylinder. The whole assembly is surrounded by lead reflector which is a simplified representation of lead lithium coolant and Booster (proposed in the original design of EURAC). The irradiation zone is the entire space outside the 2 mm iron cylinder upto a radial distance of a few cms. The beam width is 5 mm. We have calculated fluxes, helium, hydrogen deposition and energy deposition in the sample placed at various radial (R) and axial (Z) position. Table 1 gives results for neutron and proton flux and other important damage parameters. Examination of Table 1 shows that neutron fluxes are fairly constant over a large axial distance. The peak neutron flux is at $Z=3.75$ cms. Table 2 shows breakup of fluxes into different energy components. It is shown that the fluxes above 14 MeV are about 6-7% and above 40 MeV about 3-4%. But even this 3-4% of fluxes above 40 MeV accounts for more than half the helium production (Sinha 1989). The behaviour of proton flux is very different. The peak of proton flux is around $Z=19$ cms. The contribution of proton flux as a fraction of neutron flux increases upto the range of protons which is around 26 cms in lead at 600 MeV. The spreading of proton beam due to multiple coulomb scattering is responsible for this effect. The percentage of protons even though small plays important part in helium generation at large Z values. Coming to the ratio of Helium to Dpa we find that we obtain a value of around 10 at Z=3.75

Table I. Important damage parameters.

SS-316

Position R	Position Z	Flux$\times 10^{15}$ n/cm^2/sec	DPA/Yr	He appm/dpa	H appm/dpa	H/He
1.3	−1.25	2.8	120·	4.05	42.1	10.41
	3.75	7.1	361	8.21	82.5	10.05
	8.75	6.4	309	10.31	100.9	9.78
	13.75	5.1	232	21.91	155.9	7.12
	18.75	3.7	155	38.46	240.7	6.26
	23.75	2.4	87	40.46	647.8	15.89
2.3	−1.25	2.1	79	3.14	22.35	7.13
	3.75	~4.0	190	6.04	61.18	10.13
	8.75	~4.0	188	7.00	61.72	8.82
	13.75	3.7	143	7.92	73.69	9.30
	18.75	3.0	108	10.75	85.39	7.94
	23.75	2.1	68	17.15	344.30	20.07

DIN 1.4914

Position R	Position Z	He appm/dpa	H appm/dpa	H/He
1.3	−1.25	2.98	33.12	11.15
	3.75	7.52	71.40	9.49
	8.75	9.64	92.82	9.63
	13.75	21.2	143.46	6.77
	18.75	37.2	221.59	6.06
	23.75	39.81	627.23	15.75
2.3	−1.25	2.31	13.41	5.52
	3.75	5.13	55.04	10.73
	8.75	6.33	51.12	8.07
	13.75	7.22	62.87	8.70
	18.75	9.87	77.85	7.89
	23.75	16.87	348.4	20.65

cms increasing to around 40 at large Z value around $Z=23.75$ cms compared to a value of around 10-30 for different designs of fusion reactor. We have also shown values of damage parameters at $R=2.3$ cms and the damage parameters for this position also within limits. It is clear from Table 1 that a high dpa rate is obtained in most of the irradiation zone and these values are higher or comparable to FMIT values (80 dpa/yr) over a large volume. In fact, calculation for still higher radial distances such as $R=3.2$ and 4.2 cms· shows that the ratio of (Volume* Dpa) for SNS to FMIT for zones where dpa in SNS is greater than 60, is about 100 ; indicating that spallation neutrons are capable of providing

Table 2. Break-up of fluxes into different energy components.

Percentage of various energy components of neutron flux at $R=1.3$ cms in FE

E (MEV)	Particle	Z (cm) 0.5	3.75	8.75	13.75	18.75	23.75
>14	Neutron	5.3	7.25	7.38	7.24	6.98	5.80
>20	Neutron	3.04	5.54	6.13	6.15	5.96	5.11
>30	Neutron	2.22	4 51	4.97	5.17	4.89	4.10
>40	Neutron	1.67	3.70	4.22	4.44	4.17	3.26
>Proton	Proton	0.47	1.80	2.73	10.15	21.71	25.16

Percentage neutron and proton flux at $R=2.3$ cms in FE.

E	Particle	Z (cm) 0.5	3.75	8.75	13.75	18.75	23.75
>14	Neutron	3.81	5.11	5.19	4.98	4.72	4.68
>20	Neutron	2.30	3.86	4.10	4.26	4.02	4.03
>30	Neutron	1.56	2.98	3.48	3.63	3.42	3.53
>40	Neutron	1.02	2.41	2.92	3.10	2.88	2.94
Proton	Proton	0.07	0.82	1.04	1.28	3.13	7.98

100 times better Dpa and Volume combination. Taking into account the sample space where R and Z values are greater than 60 dpa/Yr, we get a sample space of about one litre leaving aside half the volume for coolant. This is the type of volume required for bulk sample testing. Coming to the primary recoil spectra we find that the fractions of recoil above 100 KeV are 12% compared to 9% for fusion spectra. The percentage of recoil above 50 kev is about 12% in the case of fusion compared to 25% in the case of SNS. These recoil energies are important from the point of view of determining nature of subcascades. It is difficult to say anything without further investigation, about the damage effects this quantitative difference will produce. Recent studies by Perlado *et al* (1989) shows that not much difference is expected in the nature of damage due to such effect. Of course compared to most other devices listed in Table 3, the similarity between SNS and fusion spectum produced recoil is much better. Coming to the problem of transmutation product we have carried out extensive studies on the evolution of transmutation product with time. Studies have been carried out to examine the effect of high energy tail (> 14 MeV) of the SNS spectrum on the time dependent evolution of new elements for Fe-56 and HT-9 alloy (Sinha and Srinivasan 1990). We have also studied the evolution of new elements in the irradiation of SS-316 and DIN 1.4914 in the radiation environment

Table 3. Comparison with different devices.

	Percentage of recoil vs damage												
	0.1		0.1 – 1.0		1.0 – 5.0		5 – 10		10 – 50		50 – 100		100
	Rec	Dam	Rec	Dam	Rec	Dam	Rec	Dam	Rec	Dam	Rec	Dam	Rec
							Nb						
Fmit	0.3	—	3.1	—	11.4	2.0	10.2	3.0	23.6	5.0	12.2	11.0	38.7
Fusion	4.4	0	20.6	0.5	30.3	3.7	13.2	4.4	19.8	18.0	2.9	8.8	8.8
Ebr-II	3.8	0	22.8	2.2	40.3	18.7	16.4	20.4	15.9	48.8	0.7	7.4	0.1
Hfir	57.2	0.1	11 4	1.1	12.1	7.3	6.4	10.3	11.0	51.0	1.6	21.6	0.3
14 Mev	0.3	0	2.9	0.1	11.0	0.4	10.1	1.4	21.4	2.0	6.2	5.0	48.1
							Cu						
Fmit	0.2	—	1.6	—	6.3	—	6.8	1	285	8	11.1	5	45.5
Fusion	5.5	0	25.2	0.5	26.5	2.7	10.3	2.9	19.5	16.7	3.6	9.2	9.4
Ebr-II	3.8	0	23.2	1.7	35.0	12.1	15.3	14.5	20.5	51.4	1.7	13.2	0.5
14 Mev	0.2	0	1.5	0	6.1	0.2	6.3	1	24.3	5	6.9	3.8	54.7

Spallation neutrons (FE-56)

Recoil Energy range	Z=0.5 cm		3.75 cm		8.75 cm		13.75 cm		18.75 cm		23.75 cm	
	Rec	Dam	Rec	Dam	Rec	Dam	Rec	Dam	Rec	Dam	Rec	Dam
<0.1 KeV	0.4	—	0.44	—	0.47	—	0.50	—	0.54	—	0.57	—
0.1 – 1.0 KeV	3.65	0.06	3.7	0.05	3.87	0.06	4.15	0.06	04.5	0.07	04.7	0.08
1 – 5 KeV	16.4	1.34	16.6	1.20	17.7	1.3	18.6	1.4	20.1	1.66	21.0	02.0
5 – 10 KeV	13.9	2.77	13.9	2.47	14.0	2.6	14.6	2.79	15.1	3.14	16.0	3.8
10 – 50 KeV	39.1	20.9	38.8	18.6	38.8	19.1	38.2	19.5	38.6	21.1	38.8	24.8
50 – 100 KeV	14.9	11.5	14.6	10.3	14.0	10.0	13.8	10.0	12.7	9.8	11.9	9.9
100 – 1000 KeV	10.2	56.9	10.9	56.0	10.2	53.9	9.25	52.0	8.22	49.7	6.59	45.8
>1000 KeV	0.376	6.5	0.74	11.4	0.8	12.9	0.8	14.2	0.8	14.5	0.67	13.6

of SNS and compared it with the evolution of elements in fusion radiation environment. It is not possible to discuss the details of this study within the limtis of this paper but it can be stated there are lot of similarities in the evolution of new materials in SNS and fusion spectrum. There are of course some new elements produced in SNS spectrum on a small scale that are not typical of fusion spectrum but as the solubility of many transmutation products is known to be much higher compared to Helium, they may not alter the damage evolution characteristics to that extent.

4. Conclusion

We have shown that charged particle beam simulation experiments are good for high dpa generation and basic physics studies but bulk properties and many radiation damage effects which are typical of fusion can not be tested. High flux reactors like HFIR, FFTF have dpa or damage rate comparable to fusion power reactors but other simulation parameters such as He/Dpa, H/Dpa and transmutation product formation differs by order of magnitude. The three proposals of accelerator based neutron sources RTNS-II, FMIT or INS have either inadequate source strength or small irradiation space or both.

It is shown than a SNS based on 600 MeV-6mA current proton accelerator meets most of the criterion for a good simulation device.

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